Long distance fiber Bragg grating strain sensor interrogation using a high speed Raman-based Fourier domain mode-locked fiber laser with recycled residual Raman pump

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Abstract: We propose a novel fiber Bragg grating (FBG) sensor interrogation using a Raman-based Fourier-domain mode locking (FDML) fiber laser for a high speed and long distance measurement. A residual Raman pump after the generation of the Raman-based FDML fiber laser is recycled for secondary signal amplification in a 2-m erbium-doped fiber (EDF) to further enhance the output power. The chromatic dispersion is precisely controlled to suppress the phase noise in the FDML laser cavity, resulting in the improvement of an R-number of 1.43 mm/dB. After recycling residual pump, we achieve the 40-km round trip transmission of the sensing probe signal with a high scan rate of 30.8 kHz. With 205-mW residual pump power, the bandwidth and the maximum gain are measured to be more than 50 nm, 10.3 dB at 1550 nm, respectively. The sensitivity of the proposed Raman-based FDML fiber laser to strain is also measured, which are 0.81 pm/µstrain in the spectral domain and 0.19 ns/µstrain in the time domain, respectively.

OCIS codes: (060.2310) Fiber optics; (060.2370) Fiber optics sensors; (060.3735) Fiber Bragg gratings; (140.3510) Lasers, fiber.

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1. Introduction

A fiber Bragg grating (FBG) has attracted great considerations in sensing applications because of their advantages such as compactness, fiber compatibility, electromagnetic immunity, and multipoint sensing capability [1]. The FBG is capable of reflecting particular wavelengths of light and transmitting all others and it is also very sensitive to external perturbation change including temperature, strain, bending, loading, and vibration [2–5]. In order to measure the wavelength shift with variations in external perturbations, the interrogation techniques, which can detect the optical intensity with respect to the wavelength shift, have been developing promisingly [6–8]. Many of these interrogation systems should employee a broadband light source and various optical filters, such as an interferometer [6], tunable filter [7], and a passive filter to convert the wavelength shift to the optical intensity change [8]. For the realization of the multiple FBG sensor interrogation system with high speed and sensitivity, the wavelength-swept fiber lasers over the spectral range of FBG sensors have been proposed [9]. When the laser is swept over the spectral range of the FBG sensors, signals reflected from FBGs are simultaneously detected by a single detector, which provides the improved performance of the optical sensing signal interrogation compared to that based on the broadband light source. However, the maximum speed of the swept rate was physically limited to a few kHz due to the filter function, the amplified stimulated emission (ASE) intensity, the saturation power, the laser gain, and cavity roundtrip time [10].

A Fourier-domain mode locking (FDML) fiber laser based on a semiconductor optical amplifier (SOA) has been developed to realize high swept speed by modulating the optical filter synchronously with the round trip time of optical signals within the laser cavity, which is very applicable to the FBG sensor interrogation [11]. However, the SOA-based FDML laser has many drawbacks, such as the undesirable ASE background, the limited wavelength tuning range, the low output power of a few mW [12]. Recently, the Raman-based FDML laser were proposed because Raman amplifiers have many advantages, such as almost no ASE background, low noise, high temperature stability, high output power, and arbitrary gain band depending on the pump wavelength [12]. In previous method [12], since the chromatic dispersion was not compensated, the proposed Raman-based FDML fiber laser has the jitter or uncertainty of the center wavelength caused by the phase noise, which results in the degradation of the ranging depth [13]. It was also not suitable for the long distance transmission of sensing probe signals because of high transmission loss of sensing probe signals [14]. For the long distance measurement by using Raman gain, the spectrum-limited FDML fiber laser was proposed [15]. However, the swept rate of the laser became low due to the long cavity length. Since the FBG was implemented to be a cavity mirror, the driving frequency of the tunable filter in the FDML laser should be precisely controlled to detect the sensing signal. In addition, it is impossible to interrogate multiple signals of sensing probes.

In this paper, a novel FBG strain sensor interrogation using a Raman-based FDML fiber laser is presented for high speed and long distance measurement. The Raman-based FDML fiber laser has a swept rate of the 30.8 kHz and a swept range of 37.2 nm. The chromatic dispersion in the FDML fiber laser cavity is precisely controlled resulting in an improved R-number of 1.43 mm/dB. The long distance measurement of the proposed sensor system is realized by recycling a residual Raman pump after Raman amplification in the FDML laser for the output power enhancement of the sensing signal. In the secondary amplification, the effective gain-band width was measured to be more than 50 nm, and the maximum gain at 1550 nm was measured to be 10.3 dB. By using the proposed Raman-based FDML fiber laser, the measured strain sensitivities in wavelength and time domains were estimated to be 0.81 pm/μstrain and 0.19 ns/μstrain, respectively. Using the proposed scheme, we can obtain typical response from the FBG sensor interrogation as a function of strain.

2. Experiments and results

2.1. FBG strain sensor interrogation based on the Raman-based FDML fiber laser with the recycled residual Raman pump

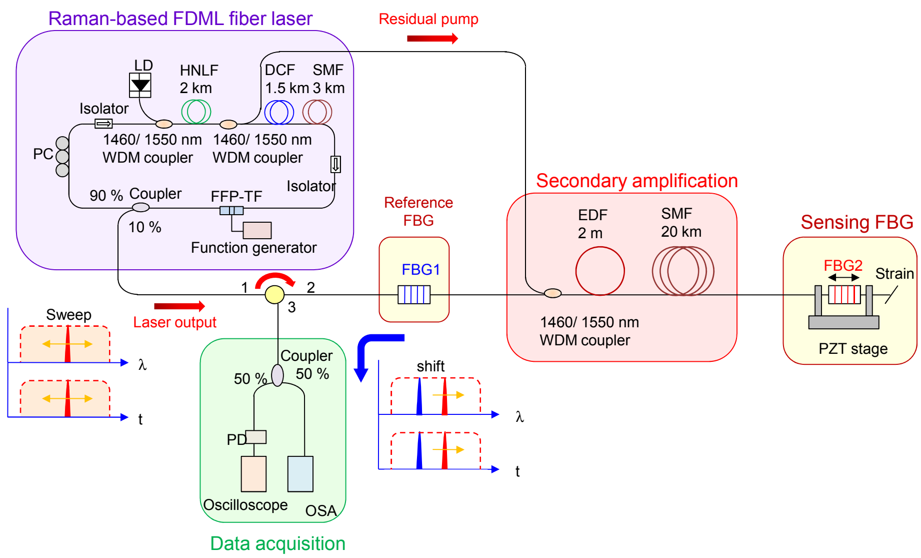

Fig. 1. Scheme for the proposed long distance FBG strain sensor interrogation using the Raman-based FDML fiber laser with the recycled residual Raman pump.

Figure 1 shows an experimental scheme for an FBG strain sensor interrogation using the Raman-based FDML fiber laser with the recycled residual Raman pump. The Raman pump laser with a power of 717-mW at 1455 nm was launched into a 2-km highly nonlinear fiber (HNLF) to induce Raman amplification. The FDML can be readily realized once a fiber Fabry-Perot tunable filter (FFP-TF) is periodically driven with a frequency equal to optical round-trip time within the laser cavity [16]. Light from one frequency sweep propagates through the cavity, and returns to the FFP-TF at the exact time when the FFP-TF is again tuned to the same frequency. An entire swept wavelength is optically stored within a long laser cavity and the FDML laser produces a train of frequency-swept signals with the spectral information in time domain. For the realization of a long distance FBG sensor interrogator, a residual pump after passing through the HNLF was recycled for the secondary amplification in the transmission line. The residual pump power of ~205 mW after the HNLF was extracted and launched into a 2-m EDF by using two 1460/1550 wavelength-division multiplexing

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(WDM) couplers. Then, the residual pump power was reused as a pump source for the secondary amplification in the EDF. FBG1 and FBG2 with center wavelengths of 1548.1 and 1549.6 nm and reflectivity of 97.2 and 94.1%, respectively, were employed. The FBG2 as the sensing probe is connected to the end of the 20-km SMF, while the FBG1 as the reference signal is inserted before the secondary amplification. The strain was applied by controlling a piezoelectric transducer (PZT) stage where the FBG2 is mounted.

The reflected signals from two FBGs are detected by using an optical spectrum analyzer (OSA) and an oscilloscope with a photo-detector (PD). The oscilloscope is triggered at the driving frequency of the FFP-TF to achieve pulse data in the same time span. When the Raman-based FDML fiber laser is repeatedly swept over the spectral range of two FBGs, a series of pulse signals in time domain reflected from two FBGs are detected at the PD. The wavelength spacing of two signals reflected from two FBGs should be changed because the center wavelength of the FBG2 as a sensing probe is shifted to longer wavelengths as the applied strain increases. It means that the time intervals between two signals monitored by the PD must be changed, which are corresponding to the wavelength spacing between two FBGs. Consequently, strain variation can be measured by acquiring the time intervals between two reflected signals from two FBGs as the proposed Raman-based FDML fiber laser is swept.

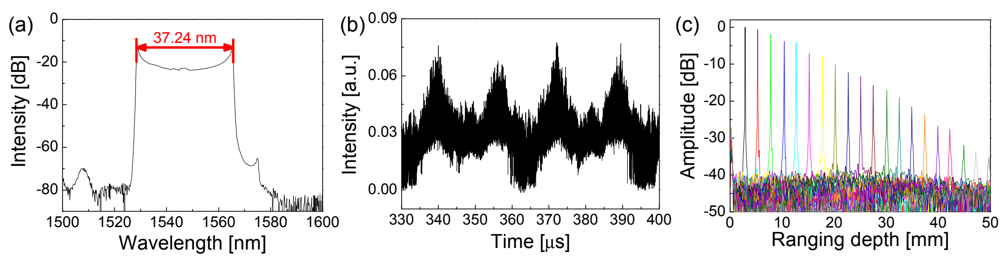

Fig. 2. (a) Output spectrum, (b) temporal transient intensity profile of the Raman-based FDML fiber laser, and (c) decay in PSFs for different arm lengths in the proposed Raman-based FDML fiber laser with the dispersion-compensated cavity.

Figure 2(a) shows the output spectrum of the Raman-based FDML fiber laser measured by the OSA. The operating frequency of the FFP-TF was set to be 30.8 kHz with respect to a total length of 6.5 km in the cavity. The full width of half maximum (FWHM) and the average minimum extinction ratio were measured to be 37.2 nm and ~55.1 dB at 1547 nm, respectively. Figure 2(b) depicts the temporal transient intensity profiles of the Raman-based FDML fiber laser. In comparison with the output characteristics of the SOA-based FDML laser, the intensity profile exhibits higher fluctuations. However, since the proposed FBG sensor interrogation system is basically exploiting the variation of the pulse interval between a reference FBG and a sensing FBG for the measurement of strain, the fluctuation of the output profile can be negligible. The chromatic dispersion in the proposed Raman-based FDML fiber laser was effectively compensated by using a 1.5-km dispersion compensating fiber (DCF) and a 3-km single mode fiber (SMF), resulting in the improvement of an R-number related with the phase noise. A Michelson interferometer was implemented to quantify the instantaneous coherence length improved by compensating the chromatic dispersion. When the FDML fiber laser is swept, the fringe patterns generated by a Michelson interferometer is converted to the point spread functions (PSFs) by performing a Fourier transform. The decay in the PSFs was exploited to evaluate the instantaneous coherence length [13]. Figure 2(c) shows the decay in the PSFs with respect to the arm difference length. The proposed Raman-based FDML fiber laser with the dispersion-compensated cavity obviously has the longer ranging depth of ~50 mm which was higher than the previous result [12]. The R-number of the proposed Raman-based FDML fiber laser was measured to be 1.43 mm/dB. We can expected that the proposed Raman-based FDML fiber laser with the

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dispersion-compensated cavity has the less uncertainty of the center wavelength, which is suitable for the accurate sensor interrogation.

2.2. Secondary amplification in the optical signal transmission line

In order to evaluate the performance of the residual Raman pump in the 20-km SMF, the overall gain was measured. As seen in Fig. 1, two 1460/1550 WDM couplers were exploited so that the residual Raman pump after the HNLF could be reused for the secondary amplification in the transmission line. The measured power of the residual Raman was 205 mW. Since the absorption band of the EDF is around 1480 nm and the EDF has the better amplification efficiency compared with the Raman amplification with the same pump power, a 2-m EDF was additionally employed as seen in Fig. 1.

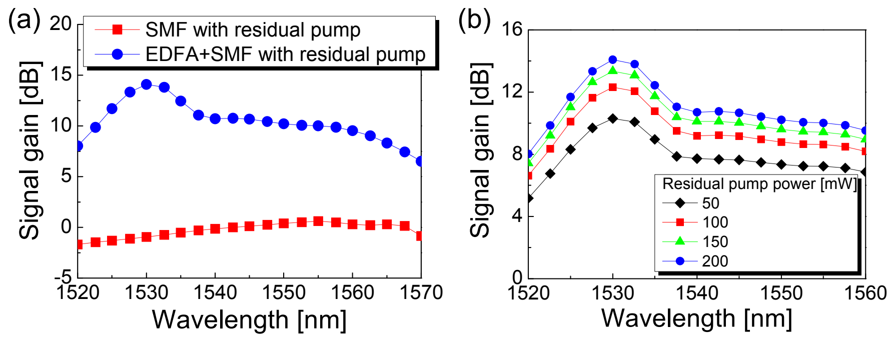

Fig. 3. (a) Measured overall gain profiles of the SMF and the EDF connected to the SMF with the recycled residual Raman pump. (b) Measured overall gain profiles of the EDF connected to the SMF with respect to variations in residual pump power.

Figure 3(a) shows the measured overall gain profiles after recycling the residual Raman pump with the SMF or the EDF connected to the SMF. The input signal level for measurement of the optical gain was ~-30 dBm. A transmission loss of the conventional SMF is typically 0.2 dB/km at 1550 nm. Since the total length of the SMF was 20 km, the total loss was measured to be 4 dB. When the residual pump was launched into the SMF only, the effective gain bandwidth was more than 25 nm over 0 dB, and the maximum gain at 1550 nm was 0.35 dB. After connecting the 2-m EDF to the SMF, the effective gain bandwidth was measured to be more than 50 nm, and the maximum gain at 1550 nm was 10.3 dB. Compared with the signal without the residual pump recycled configuration, the signal amplified by using the recycled residual Raman pump with the 2-m EDF is as high as 14.3 dB. As the residual pump power was changed from 50 to 200 mW, the overall gain profiles of the EDF connected to the SMF were observed as shown in Fig. 3(b). Therefore, using the secondary amplification with the recycled residual Raman pump, the sensing distance can be significantly increased. In previous sensing schemes [17, 18], it is necessary to utilize an optical spectrum analyzer for the sensing signal interrogation resulting in slow measurement speed. To increase the number of sensing probes, multiple photodetectors for their signal interrogation should be employed inevitably. The proposed scheme, however, is capable of measuring multipoint strain in high speed by using a single photodetector because it exploits the high speed FDML fiber laser with the high swept rate. It is noticeable that the transmission distance can be further increased because with the given residual pump power the signal gain is not saturated. We could estimate a maximum round trip distance of more than 90 km by considering the signal gain and the transmission loss of the SMF in the present experimental condition. To increase the transmission distance of the order of hundreds km, the experimental parameters, such as the cavity loss of the FDML fiber laser, the efficiency in the pump power, the length of the gain medium, insertion losses of all components, etc., should be optimized.

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2.3. Strain measurement using the proposed Raman-based FDML with the recycled residual Raman pump

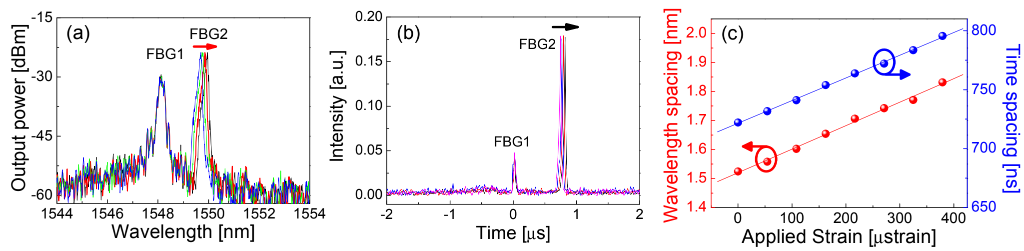

Fig. 4. Measured output spectra in wavelength (a) and time (b) domains, respectively, and (c) variations in Wavelength spacing and time interval as a function of strain.

Figure 4(a) and 4(b) depict output spectra in wavelength and time domains, respectively, as strain the applied to the FBG2 as a sensing probe increases. The center wavelength of the FBG2 was shifted to longer wavelengths with variations in strain, which should change the time spacing between two reflection peaks. Variations in the wavelength spacing and the time spacing as a function of strain were shown in Fig. 4(c), respectively. When the applied strain was 380 μstrain, the variation of the wavelength spacing and the corresponding time spacing were ~0.3 nm and ~74 ns, respectively. The strain sensitivities in wavelength and time domains were measured to be 0.81 pm/μstrain and 0.19 ns/μstrain, respectively. Therefore, it is clearly evident that the long distance strain measurement over the 40-km round transmission can be realized effectively by using the proposed FBG strain sensor interrogation system, which is not achievable in the previous FDML-based sensing techniques [11]. Since the proposed strain sensing probe based on the FBG is affected by strain and temperature simultaneously, it is important to discriminate two concurrent sensitivities. By implementing the specially designed FBG-based sensing probes in the proposed sensing scheme [19], we can obtain the temperature-insensitive, long distance strain sensor based on the proposed Raman-based FDML laser with the recycled residual Raman pump.

3. Conclusion

A long distance FBG sensor interrogation using a high-speed Raman-based FDML fiber laser with recycled residual Raman pump has been demonstrated. The Raman-based FDML fiber laser exhibited the high performance in terms of the 30.8-kHz swept rate and 37.2-nm swept range. The chromatic dispersion with the laser cavity was precisely controlled, which results in the improvement of an R-number of 1.43 mm/dB. The residual pump power after the generation of the Raman-based FDML fiber laser was extracted and recycled into the transmission line and the secondary amplification was successfully obtained. After the 40-km round trip transmission of the SMF, sensing signals could be effectively detected, which was impossible in the previous FDML-based sensing interrogation method [11]. The variations in strain was also measured by monitoring the time interval corresponding to the wavelength spacing between two reflected signals from two FBGs using the proposed Raman-based FDML fiber laser. The measured strain sensitivities in wavelength and time domains were measured to be 0.81 pm/μstrain and 0.19 ns/μstrain, respectively. We believed that the proposed Raman-based FDML fiber laser with recycled residual Raman pump is very useful for the high speed and long distance FBG sensor system.

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